Naval Research Laboratory
Monterey, CA 93943-5502

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Quality Control of Meteorological Observations at Fleet Numerical Meteorology and Oceanography Center

NANCY L. BAKER

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Nancy L. Baker

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Meteorological observations are subjected to extensive objective quality control (QC) before they are stored in the operational atmospheric data base at Fleet Numerical Meteorology and Oceanography Center (FNMOC, Monterey, CA). This QC identifies erroneous observations that could adversely affect the quality of operational products produced by the Navy's global and regional atmospheric prediction models and stratospheric analysis. These QC procedures have recently been substantially modified and improved. This report describes the QC system currently in use operationally with the Navy Operational Global/Regional Atmospheric Prediction Systems (NOGAPS/NORAPS) on the FNMOC supercomputers. A primary change was the inclusion of the Complex QC developed at the National Meteorological Center; other QC procedures were updated to reflect those in use at the European Center for Medium-range Weather Forecasts.

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QUALITY CONTROL OF METEOROLOGICAL OBSERVATIONS AT FLEET NUMERICAL METEOROLOGY AND OCEANOGRAPHY CENTER

INTRODUCTION

Meteorological observations are subjected to extensive objective quality control prior to storage in an operational atmospheric database at Fleet Numerical Meteorology and Oceanography Center (FNMOC). The quality controlled observations are used by the Navy's global and regional atmospheric prediction models and by the stratospheric analysis. The atmospheric analyses and models produce numerical guidance and products in support of a wide range of Navy atmospheric and oceanographic requirements. Quality control (QC) of the meteorological observations is vitally important to identify erroneous observations that can adversely affect the quality of these operational products.

The observations that are processed are from a variety of sources. Each observing platform has its own unique error characteristics which must be taken into consideration. The conventional sources include radiosonde observations of height, temperature, moisture and wind; pibal and aircraft wind reports; and pressure, wind, temperature and moisture observations from ships, fixed and drifting buoys, and land stations. The satellite-derived observations include temperature sounding retrievals, moisture retrievals, cloud-tracked winds, and sea-surface wind speeds.

The quality control of meteorological observations for the operational atmospheric database consists of four main components. These four components are pre-analysis objective quality checks, checks within the analysis for consistency against the background and with neighboring observations, subjective evaluation of marine observations, and finally, the determination and correction of observational biases such as the radiative errors of radiosondes.

The quality control procedures were developed by the Marine Meteorology Division of the Naval Research Laboratory (NRL). Baker (1992a;1992c) describes the objective quality control procedures that were developed in support of the Navy Operational Global Atmospheric Prediction System (NOGAPS) version 3.0. The quality control procedures have been substantially modified and improved since that time. This NRL report describes the changes that have been made to the objective quality control, and documents the procedures now used operationally with NOGAPS 3.3 and NORAPS (Navy Operational Regional Atmospheric Prediction System) on the FNMOC supercomputers.

The subsequent checks against the analysis background and for consistency with surrounding observations made in the multivariate optimum interpolation analysis are discussed in Goerss and Phoebus (1993;1991). The details pertaining directly to the implementation of the quality control system at FNMOC are presented in Baker (1992b). These details include the data formats, manual quality control procedures, and the statistical database and methods used for the identification and correction of observational biases.

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Table 1: Quality Flag Definitions

Quality Flag	Interpretation
0	QC not done
1	good
2	suspect
3	bad
4	original value corrected
5	original value corrected; later flagged suspect
6	value substituted for missing
7	value substituted for missing; later flagged suspect
9	missing

OBJECTIVE QUALITY CONTROL

The quality checking procedures for meteorological observations have traditionally been derived from a series of rules. Many of the rules are based upon geophysical limitations, such as checks against extreme observed values and checks for hydrostatic consistency. Other rules are derived from the World Meteorological Organization (WMO) standards for the exchange of meteorological observations (WMO, 1988). The checks developed from these rules are typically applied sequentially, and the information gleaned from one test is not used in a subsequent test. Recently, a group at the National Meteorological Center led by W. Collins and L. Gandin have developed a new, innovative QC technique called "Complex Quality Control". The basic premise of Complex QC (CQC) is that final quality decisions are not made until all of the validation checks have been completed. Then, the test results are examined and a final decision is made about the quality of a given observation. The new, operational QC at FNMOC includes NMC's CQC (Collins and Gandin 1990) as well as traditional sequential tests based on those in use at the European Center for Medium-range Weather Forecasts (Norris 1990).

Quality Flags

The updated objective quality control procedures follow Norris (1990) and define the quality flags in terms of confidence (in percent) rather than the discrete quality flags used in the previous version. This allows for better distinction between suspect and reject data. Each parameter or observation within a report has an associated confidence quality indicator ranging from 0% (no confidence in the report) to a maximum confidence of 100%. Counters are also kept that indicate how many tests the observation has failed (the fail counter) or passed (the pass counter). For some tests, the confidence is adjusted according to how many tests the parameter has failed or passed already. The initial confidences are set to 70%. The operational multivariate optimum interpolation still relies upon the old discrete quality flags. At the conclusion of the testing, the confidence values are converted a final quality flag value that varies according to data type; the details are found in corresponding sections. The final discrete quality flags are defined in Table 1.

The quality checks are presented in the following sections. After each test are three numbers in parentheses specifying the confidence increase or decrease (in percent), the change to the fail counter and the change to the pass counter. An asterisk (*) in the confidence column indicates that

Table 2: Adjustments to Parameter Confidences

Pass counter value	1	2	3	4	5	> 5
Confidence increment	5	4	3	2	1	0
Fail counter value	1	2	3	4	5	> 5
Confidence increment	-10	-25	-20	-15	-10	0

the parameter confidence is adjusted according to the value of the pass counter (if the observation passed the test) or fail counter (if the observation failed the test). This adjustment to the confidence is given in Table 2.

The parameters listed in the following sections are in standard WMO notation. The reader is referred to WMO (1988) for parameter definitions and code tables. Several tests, such as the checks against gross error limits, may apply to several different parameters. For these test descriptions, PV denotes the parameter value.

SURFACE REPORTS

All observations are checked against plausibility or gross error limits. The gross error tolerances are set slightly greater or smaller than the record observed maximum or minimum values for a parameter. For example, the minimum and maximum plausibility limits for land temperatures are -90 °C and 60 °C, respectively. Historically, the minimum recorded temperature was -89 °C at Vostok, Antarctica and the maximum recorded temperature was 58 °C at El Azizia, Libya (Riordan and Bourget, 1985). The limits vary between summer and winter, as well as poleward or equatorward of 45°. The observations are also checked for internal consistency. An example of a violation of internal consistency would be a station reporting temperatures well above freezing and snow falling. Station pressures are not quality checked at the present time since the FNMOC raw data file, ADPFILE, does not store the hundreds or thousands digit for pressure.

No substitutions are provided for erroneous surface data except for ship position which may be corrected as a result the operational ship tracking program at FNMOC. Based upon its previously reported positions, the allowable region for a ship's location is calculated. Ships that report a position outside of this region may have their position corrected, or the ship position QC flag set to reject. The new position must resemble the position originally reported, i.e. 25.2 °N, 130.0 °E could be replaced with 25.2 °N, 130.0 °W. The reports are subjectively evaluated if only two reports from the same ship are available and they are in disagreement.

The DMSP/SSMI (Special Sensor Microwave Imager) geophysical data records contain sea surface wind speeds and various moisture parameters. The SSMI observations are quality controlled prior to storage in the raw observational database. Any observation that falls outside reasonable limits is predefined by the original processing to be out-of-limits, and both value and quality flag are set to missing.

Limit Checks for Surface Observations

$PV < min2$ or $PV > max2$ .... $(-60; +1; 0)$ fail PV
$min2 \leq PV < min1$ or $max1 < ppp \leq max2$ .... $(-30; 0; 0)$ for PV
$min1 \leq PV \leq max1$ .... $(0; 0; +1)$ pass PV

The maximum and minimum permitted limits are given for sea level pressure in Table 3; for geopotential heights in Table 4; for wind speed in Table 5; for temperature in Table 6; for dew-point in Table 7; for pressure tendency in Table 8; and for sea surface temperature in Table 9.

Internal Consistency Checks for Wind Direction dd and Speed FF

$dd < 0$ or $dd > 360$ .... (-100;+1;0) fail dd
dd missing, FF not missing .... (*;+1;0) fail FF
dd not missing, FF missing .... (*;+1;0) fail dd
$dd \neq 0, FF = 0$ .... (*;+1;0) fail dd, FF
$dd = 0,\ 3 < FF \leq 6\mathrm{m\,s^{-1}}$ .... (*;+1;0) fail dd and (-30;0;0) for FF
$dd = 0,\ FF > 6\,\mathrm{m\,s^{-1}}$ .... (*;+1;0) fail dd and (-60;+1;0) fail FF
$dd = 0,\ FF \leq 3\mathrm{m\,s^{-1}}$ .... (*;0;+1) pass dd, FF

Internal Consistency of Temperature TT, Dewpoint T_dT_d and Present Weather ww

If $TT > T_dT_d + 5$ °C and $42 \leq ww \leq 49$ .... (*;+1;0) fail TT, T_dT_d, ww
Else .... (*;0;+1) pass TT, T_dT_d, ww
If $TT < -2$ °C and $50 \leq ww \leq 55$ or $58 \leq ww \leq 65$
or $68 \leq ww \leq 69$ or $80 \leq ww \leq 82$ .... (*;+1;0) fail TT, ww
Else .... (*;0;+1) pass TT, ww
If $TT > 5$ °C and $68 \leq ww \leq 79$ or $83 \leq ww \leq 88$ .... (*;+1;0) fail TT, ww
Else .... (*;0;+1) pass TT, ww
Land only:
If $TT < T_dT_d$ or $TT - T_dT_d > 50$ °C .... (*;+1;0) fail TT, T_dT_d
Else .... (*;0;+1) pass TT, T_dT_d
Sea only:
If $TT < T_dT_d - 1$ °C or $TT - T_dT_d > 30$ °C .... (*;+1;0) fail TT, T_dT_d
Else .... (*;0;+1) pass TT, T_dT_d

Internal Consistency of Pressure Tendency Characteristic a, and Magnitude ppp

$a < 0$ or $a > 8$ .... (-100;1;0) for a
If $ppp = 0$ and $a \neq 0, 4$ or 5 .... (*;+1;0) fail ppp, aa
Else .... (*;0;+1) pass ppp, aa
If $a = 4$ and $ppp \neq 0$ .... (*;+1;0) fail ppp, aa
Else .... (*;0;+1) pass ppp, aa

The confidence values are converted to the final quality flags as specified in Table 10. The final wind QC flag is assigned according to the minimum of the wind direction and wind speed confidence values. The final pressure tendency QC flag is assigned according to the minimum of the pressure tendency characteristic and magnitude confidence values. The quality flags for pressure and wind from the FNMOC manual quality control overwrite the objective QC flags.

Table 3: Mean Sea Level Pressure Limits (hPa)

	Winter				Summer			
Area	min2	min1	max1	max2	min2	min1	max1	max2
45S - 45N	870	910	1080	1100	850	900	1080	1100
45N - 90N and 45S - 90S	880	910	1080	1100	880	920	1080	1100

Table 4: Geopotential Height Limits (m) for Surface Reports

	Area 45S - 45N				Area 45N - 90N; 45S - 90S			
Level(hPA)	min2	min1	max1	max2	min2	min1	max1	max2
850	0	200	2000	2200	200	400	2000	2200
700	2200	2350	3450	3600	2300	2450	3450	3600
500	4500	4700	6100	6300	4500	4700	6100	6300

Table 5: Surface Wind Speed Limits (m/s)

	Winter				Summer			
Area	min2	min1	max1	max2	min2	min1	max1	max2
45S - 45N	0	0	60	125	0	0	90	150
45N - 90N and 45S - 90S	0	0	50	100	0	0	40	75

Table 6: Surface Temperature Limits (°C)

	Winter				Summer			
Area	min2	min1	max1	max2	min2	min1	max1	max2
45S - 45N	-40	-30	50	55	-30	-20	50	60
45N - 90N and 45S - 90S	-90	-80	35	40	-40	-30	40	50

Table 7: Surface Dew Point Limits (°C)

	Winter				Summer			
Area	min2	min1	max1	max2	min2	min1	max1	max2
45S - 45N	0	0	60	125	0	0	90	150
45N - 90N and 45S - 90S	0	0	50	100	0	0	40	75

Table 8: Mean Sea Level Pressure Tendency Limits (hPa)

	Winter				Summer			
Area	min2	min1	max1	max2	min2	min1	max1	max2
45S - 45N	-50	-40	40	50	-50	-40	40	50
45N - 90N and 45S - 90S	-50	-40	40	50	-50	-40	40	75

Table 9: Sea Surface Temperature Limits (°C)

	Winter				Summer			
Area	min2	min1	max1	max2	min2	min1	max1	max2
45S - 45N	0	2	32	35	0	2	32	35
45N - 90N and 45S - 90S	-2.1	-1	27	30	0	-1	30	35

Table 10: Conversion from Confidence Values to Quality Flags for Surface Observations

Confidence value (percent)	Quality Flag
70 - 100	1: good
24 - 69	2: suspect
0 - 23	3: bad

Aircraft Reports

The checks described in this section are applied to both conventional *aireps* and the newer automated *ACARS* (AIRINC (Aeronautical Radio, Inc.) Communications Addressing and Reporting System) reports. All observations are checked against climatological limits, as well as for internal consistency. No substitutions are provided for erroneous observations.

Limit Checks for Geopotential Height HHH

$HHH < 10$ m or $HHH > 25,000$ m .... (-60;1;0) fail HHH
and .... (-30;0;0) for TT, dd, FF

Limit Checks for Air Temperature TT and Wind Speed FF

$PV < min2$ or $PV > max2$ .... $(-60; +1; 0)$ fail PV
$min2 \leq PV < min1$ or $max1 < ppp \leq max2$ .... $(-30; 0; 0)$ for PV
$min1 \leq PV \leq max1$ .... $(0; 0; +1)$ pass PV

The limits depend on HHH and are given in Table 11 for temperatures and in Table 12 for wind speeds.

Internal Consistency Checks for Wind Direction and Speed dd, FF

$dd < 0$ or $dd > 360$ .... (-100;+1;0) fail dd
dd missing, FF not missing .... (*;+1;0) fail FF
dd not missing, FF missing .... (*;+1;0) fail dd
$dd \neq 0, FF = 0$ .... (*;+1;0) fail dd, FF
$dd = 0$, $3 < FF \leq 6\,\mathrm{m\,s^{-1}}$ .... (*;+1;0) fail dd and (-30;0;0) for FF
$dd = 0$, $FF > 6\,\mathrm{m\,s^{-1}}$ .... (*;+1;0) fail dd and (-60;+1;0) fail FF
$dd = 0$, $FF \leq 3\,\mathrm{m\,s^{-1}}$ .... (*;0;+1) pass dd, FF

The following checks were added based upon personal experience, and are performed after the above checks have been completed. These tests set the quality flag directly.

For Aireps;
$dd = 0$ and $FF \geq 0$ .... QC = 3
$dd = 360$ and $FF = 0$ .... QC = 2

For ACARS;
$dd > 0$ and $FF = 0$ .... QC = 3
$dd = 0$ and $FF > 0$ .... QC = 2

The confidence values are converted to quality flags according to Table 13. The final wind QC flag is assigned according to the minimum of the wind direction and wind speed confidence values.

SATELLITE CLOUD-TRACKED WINDS

All observations are checked against climatological limits, as well as for internal consistency. No substitutions are provided for incorrect observations.

Table 11: Limits Values for Temperature at Different Levels (°C)

		Area 45S - 45N				Area 45N - 90N, 45S - 90S			
Level (hPa)	Level (gpm)	min2	min1	max1	max2	min2	min1	max1	max2
1100	-600	-50	-30	50	60	-90	-70	40	50
1000	300	-50	-30	50	60	-90	-70	40	50
850	1500	-65	-50	30	40	-90	-70	20	30
700	3000	-80	-70	20	30	-90	-70	10	20
500	5500	-95	-80	5	10	-100	-80	-5	5
400	7000	-100	-85	-5	0	-100	-85	-10	-5
300	9000	-100	-85	-10	-5	-100	-85	-10	-5
250	10000	-100	-85	-10	-5	-100	-85	-10	-5
200	12000	-100	-85	-10	-5	-100	-85	-10	-5
150	14000	-100	-85	-10	-5	-100	-85	-10	-5
100	16500	-100	-85	-10	-5	-100	-85	-10	-5
70	18500	-100	-85	-5	5	-100	-85	-5	5
50	20000	-100	-85	-5	5	-100	-85	-5	5
30	22000	-100	-85	-5	5	-100	-85	-5	5
20	26000	-100	-85	-5	5	-100	-85	-5	5
10	30000	-100	-85	-5	5	-100	-85	-5	5
7	33000	-90	-80	10	20	-90	-80	10	20
5	36000	-80	-70	15	30	-80	-70	15	30
3	39000	-70	-60	25	35	-70	-60	25	35
2	42000	-70	-60	30	40	-70	-60	30	40
1	48000	-70	-60	30	40	-70	-60	30	40
0.1	99999	-70	-60	30	40	-70	-60	30	40

Table 12: Limits Values for Wind Speed at Different Levels ($\mathrm{m\,s^{-1}}$)

		Area 45S - 45N				Area 45N - 90N, 45S - 90S			
Level (hPa)	Level (gpm)	min2	min1	max1	max2	min2	min1	max1	max2
1100	-600	0	0	60	100	0	0	60	100
1000	300	0	0	60	100	0	0	40	100
850	1500	0	0	65	100	0	0	20	100
700	3000	0	0	70	100	0	0	10	100
500	5500	0	0	100	120	0	0	-5	120
400	7000	0	0	130	150	0	0	-10	150
300	9000	0	0	160	180	0	0	-10	180
250	10000	0	0	160	180	0	0	-10	180
200	12000	0	0	160	180	0	0	-10	180
150	14000	0	0	150	170	0	0	-10	170
100	16500	0	0	150	170	0	0	-10	170
70	18500	0	0	150	170	0	0	-5	170
50	20000	0	0	150	170	0	0	-5	170
30	22000	0	0	90	110	0	0	-5	110
20	26000	0	0	90	110	0	0	-5	110
10	30000	0	0	75	95	0	0	-5	95
7	33000	0	0	80	100	0	0	10	100
5	36000	0	0	120	140	0	0	15	140
3	39000	0	0	150	170	0	0	25	170
2	42000	0	0	200	220	0	0	30	220
1	48000	0	0	200	220	0	0	30	220
0.1	99999	0	0	200	220	0	0	30	220

Table 13: Conversion from Confidence Values to Quality Flags for Aircraft Observations

Confidence value (percent)	Quality Flag
70 - 100	1: good
35 - 69	2: suspect
0 - 34	3: bad

Table 14: Conversion from Confidence Values to Quality Flags for Satellite Cloud-tracked Winds

Confidence value (percent)	Quality Flag
70 - 100	1: good
47 - 69	2: suspect
0 - 46	3: bad

Limit Checks for Atmospheric Pressure *ppp*

$ppp < 0$ or $ppp > 1080$ hPa .... (-100;+1;0) fail *ppp*

Limits Checks for Temperature and Wind Speed

$PV < min2$ or $PV > max2$ .... $(-60;+1;0)$ fail PV
$min2 \leq PV < min1$ or $max1 < ppp \leq max2$ .... $(-30;0;0)$ for PV
$min1 \leq PV \leq max1$ .... $(0;0;+1)$ pass PV

The limits depend on pressure level and are given in Table 11 for temperatures and in Table 12 for wind speeds.

Internal Consistency Checks of Wind Direction *dd* and Speed *FF*

$dd < 0$ or $dd > 360$ .... (-100;+1;0) fail dd
dd missing, FF not missing .... (*;+1;0) fail FF
dd not missing, FF missing .... (*;+1;0) fail dd
$dd \neq 0, FF = 0$ .... (*;+1;0) fail dd, FF
$dd = 0$, $3 < FF \leq 6\,\mathrm{m\,s^{-1}}$ .... (*;+1;0) fail dd and (-30;0;0) for FF
$dd = 0$, $FF > 6\,\mathrm{m\,s^{-1}}$ .... (*;+1;0) fail dd and (-60;+1;0) fail FF
$dd = 0$, $FF \leq 3\,\mathrm{m\,s^{-1}}$ .... (*;0;+1) pass dd, FF

The confidence values are converted to quality flags according to Table 14. The final wind QC flag is assigned according to the minimum of the wind direction and wind speed confidence values.

SATELLITE SOUNDINGS

All observations are checked against climatological limits, as well as for internal consistency. The confidence values for each parameter and level are converted to quality flags according to Table 15. Due to limitations with the current format of satellite soundings within the database, the quality flags for the individual levels are not retained. Rather, the entire sounding is assigned an overall quality flag. Any "suspect" error in any of the parameters or levels results in a quality flag of "suspect"; any "fail" error results in a quality flag of "bad". No substitutions are provided for erroneous data.

Check Pressures for each Level

Base pressure $p_a p_a < 0$ or $p_a p_a > 1080$ mb .... (-100;+1;0) fail $p_a p_a$
Upper pressure $p_i p_i < 0$ or $p_i p_i > 1080$ mb .... (-100;+1;0) fail $p_i p_i$

Table 15: Conversion from Confidence Values to Quality Flags for Satellite Soundings

Confidence value (percent)	Quality Flag
70 - 100	1: good
35 - 69	2: suspect
0 - 34	3: bad

Limit Checks for Layer Mean Temperature, Precipitable Water, and Thickness

$PV < min2$ or $PV > max2$ .... $(-60; +1; 0)$ fail PV
$min2 \leq PV < min1$ or $max1 < ppp \leq max2$ .... $(-30; 0; 0)$ suspect PV
$min1 \leq PV \leq max1$ .... $(0; 0; +1)$ pass PV

The thickness limits (TL) are derived from the temperature limits using the formula

$$TL = (R/g) * ((T_i + T_{i+1})/2) * ln(p_i/p_i + 1). \tag{1}$$

The temperature limits are given in Table 11 and are the average of the limits over the layer. The precipitable water limits are given in Table 16 and are the sum of the limits over the layer. The pressure level limits may be interpolated linearly in *ln p* if necessary.

RADIOSONDE OBSERVATIONS

Radiosonde observations determine the vertical temperature and humidity profiles of the atmosphere as a function of pressure. A rawinsonde report includes wind velocity measurements as well. The term, radiosonde, commonly refers to either type of report. Pilot balloons or PIBALs are measurements of wind speed and direction only, as a function of height and/or pressure. They are discussed in the section PILOT BALLOON REPORTS. Radiosondes are probably the single most important observation source available. For this reason, the most effort is expended on them and they are discussed in greater detail here.

The WMO has established rules for the international exchange of radiosonde observations. Specific criteria apply to the selection of mandatory and significant levels in a radiosonde observation. For example, all stations must report mandatory level information. In addition, a sufficient number of significant levels must be selected so that the reported sounding reproduces the recorded sounding trace to within certain limits. Requirements also exist for the delineation of significant inversions. These rules provide the basis for many of the radiosonde quality checks of this section.

The radiosonde quality control procedures have been substantially modified from the previous operational version described in Baker (1992a, 1992b). The Complex Quality Control (CQC) code was obtained from the National Meteorological Center (NMC) and modified for use with the FNMOC observation and field database. The CQC code is thoroughly documented in Collins and Gandin (1992) and will be only briefly discussed here. The remaining radiosonde quality control modules follow the ECMWF procedures documented in Norris (1990), and are also described within this report. The new ECMWF quality control differs from the previous version (see Baker 1992b) in that the discrete quality flags are replaced with continuous confidence values. Some of the tests that didn't perform well have been removed, and less effort is expended to determine errors based upon

Table 16: Limit Values for Precipitable Water for Layers Between Mandatory Pressure Levels

		Area 45S - 45N				Area 45N - 90N, 45S - 90S			
Level (hPa)	Level (gpm)	min2	min1	max1	max2	min2	min1	max1	max2
1100	-600	0	0	100	150	0	0	100	150
1000	300	0	0	100	150	0	0	100	150
850	1500	0	0	40	60	0	0	40	60
700	3000	0	0	30	45	0	0	30	45
500	5500	0	0	20	30	0	0	20	30
400	7000	0	0	15	25	0	0	15	25
300	9000	0	0	10	15	0	0	10	15
250	10000	0	0	5	8	0	0	5	8
200	12000	0	0	1	2	0	0	1	2
150	14000	0	0	1	2	0	0	1	2
100	16500	0	0	1	2	0	0	1	2
70	18500	0	0	1	2	0	0	1	2
50	20000	0	0	1	2	0	0	1	2
30	22000	0	0	1	2	0	0	1	2
20	26000	0	0	1	2	0	0	1	2
10	30000	0	0	1	2	0	0	1	2
7	33000	0	0	1	2	0	0	1	2
5	36000	0	0	1	2	0	0	1	2
3	39000	0	0	1	2	0	0	1	2
2	42000	0	0	1	2	0	0	1	2
1	48000	0	0	1	2	0	0	1	2
0.1	99999	0	0	1	2	0	0	1	2

data from the surrounding levels. Only the Complex QC is now allowed to generate replacements for erroneous observations. Operationally, the Complex QC is performed first and is followed by the sequential ECMWF QC.

Complex Quality Control

The basic premises of CQC are that the system is automated and designed specifically for each observing platform and each parameter. All of the quality checks are performed first, followed by a decision-making algorithm which detects and either corrects or rejects "rough" errors. Rough errors are those that are due to some definite cause. Examples of rough errors are the human mistakes that can occur while making the observation, or during processing and communicating of the observation. Most rough errors are "simple" errors, for example mistakes in a single digit, temperature sign, or the transposition of two digits.

The results of the tests are quantified in a set of residuals which reflect the degree of inconsistency of the parameter in question. For radiosondes, the redundancy between the geopotential heights and temperatures allows the hydrostatic equation to be used to detect rough errors. The hydrostatic residual is the difference between the layer thickness computed from the geopotential heights and the thickness computed hydrostatically from the temperatures. The hydrostatic residuals may also be formed in terms of temperature. The Complex QC also calculates a baseline residual which is the difference between the station elevation given in the Master Station Catalog (see Baker 1992b) and the station elevation computed hydrostatically from surface pressure and the lowest two reported heights. This residual may also be formed in terms of surface pressure.

The remaining three residuals are the statistical check residuals. They are the difference between the observed and forecast first guess (the increment); the difference between the increment and its value interpolated from neighboring stations (the horizontal resuidual); and the difference between the increment and its value interpolated from two surrounding levels (the vertical residual). These residuals may be formed in terms of heights or temperatures (or reduced mean sea level pressure where applicable). The checks utilizing these residuals are used primarily to confirm or deny corrections proposed by the hydrostatic and baseline checks.

The decision-making algorithm examines the magnitude and sign of the hydrostatic residuals for three adjacent layers in order to detect erroneous data. When errors are found, corrections are proposed and tested. If the correction causes the statistical check residuals to become acceptably small, a confident correction is made and the initial confidence is set to 90%. Otherwise, the initial confidence (based on CQC results) is set to 70% for observations flagged as good, 36% for observations flagged as suspect, and 10% for observations flagged as reject.

An example of a simple temperature correction is presented in Table 17. In this example, a temperature of −7.9 °C was reported at 100 hPa. The first guess interpolated to the observation location was −48.9 °C, and the temperature residuals were all very close to 40 °C. The decison-making algorithm made a confident correction of 40.0 °C with the new corrected temperature of −47.9 °C.

A simple height correction is illustrated in Table 18. The reported height of 12040 m at 200 hPa produces height residuals between -70 and -84 m. The decision-making algorithm provides a simple correction of 100 m, which is equivalent to a single digit correction in the hundreds place.

Table 17: Example of a Simple Temperature Correction by Complex QC

Station id: 24266 Lat: 67.6 Lon: 113.4 Elev: 137. Date/time: 94/06/23/00												
	Observation		Increment		Hydros. Res.		Vertical		Horizontal		Guess	
Pressure	Z	T	Z	T	Z	T	Z	T	Z	T	Z	T
200	11890	-51.5	-2	0.2	-19	-5.9	-13	0.8	8	-1.0	11892	-51.7
150	13780	-47.9	8	1.5	8	2.0	2	-5.0	16	1.2	13772	-49.4
100	16460	**-7.9**	22	41.0	-231	-38.9	3	40.4	22	39.4	16438	-48.9
70	18830	-47.1	42	1.9	-195	-37.3	14	-5.9	32	0.4	18788	-49.0
50	21060	-45.9	53	2.0	-2	-0.5	31	1.6	32	1.1	21007	-47.9

Decision-making results				
Pressure	Variable	Old Value	New Value	Correction
100	T	-7.9	-47.9	-40.0

Table 18: Example of a Simple Geopotential Height Correction by Complex QC

Station id: 12425 Lat: 51.1 Lon: 17.0 Elev: 116. Date/time: 94/06/23/00												
	Observation		Increment		Hydros. Res.		Vertical		Horizontal		Guess	
Pressure	Z	T	Z	T	Z	T	Z	T	Z	T	Z	T
250	10680	-48.5	-1	0.9	-1	-0.3	25	0.7	-6	-1.4	10681	-49.4
200	**12040**	-55.7	-71	1.6	-84	-25.7	-70	1.4	-72	1.8	12111	-57.3
150	13920	-59.1	0	-0.3	63	15.0	26	-1.1	3	0.1	13920	-58.8
100	16490	-54.1	8	2.4	0	0.0	1	2.5	3	1.0	16482	-56.5

Decision-making results				
Pressure	Variable	Old Value	New Value	Correction
200	Z	12040.0	12140.0	100.0

Climatological Limits Checks

The geopotential heights, temperatures, dewpoint depressions and wind speed are compared against climatological or gross error limits. The limits depend on pressure and are given in Tables 11 through 12. The limits tests are given below.

$PV < min2$ or $PV > max2$ .... $(-60; +1; 0)$ fail PV
$min2 \leq PV < min1$ or $max1 < ppp \leq max2$ .... $(-30; 0; 0)$ for PV
$min1 \leq PV \leq max1$ .... $(0; 0; +1)$ pass PV

Lapse Rate and Inversion Checks of Temperature Profiles

The vertical temperature profile in the sounding is checked for unreasonable lapse rates and excessive inversions. The sounding is scanned layer by layer from the surface to the highest level. All mandatory and significant level temperature data are used unless the pressure confidence value is less than 24%. The lapse rate is allowed to be somewhat superadiabatic in the lower levels of the atmosphere. Extreme inversions are not permitted. If an unlikely lapse rate is detected, an attempt is made to determine which temperature is in error by examining the adjacent layers. For each layer the following steps are followed:

Test for Inversions

$T_{i+1} - T_i > invmax$ .... (*;+1;0) fail T_{i+1}, T_i

The limits, *invmax*, are given by Table 19 for inversion over thin pressure layers and Table 20 for inversions over thick pressure layers. Thin pressure layers are defined to have less than 10 hPa pressure difference between the two levels. However, if the pressure of the base of the layer is greater than 850 hPa, the layer is defined to be thin for pressure differences is less than 20 hPa.

Check for Unreasonable Lapse Rates

Use the temperature T_i at pressure p_i to extrapolate a new temperature T'_{i+1} at the pressure level p_{i+1} by the dry adiabatic lapse rate,

$$T'_{i+1} = T_i(p_{i+1}/p_i)^{R/C_p} - supcor \tag{2}$$

where *supcor* is the superadiabatic correction given by Table 21.

The computed temperature T'_{i+1} is compared with the reported temperature T_{i+1}. If $T_{i+1} \geq T'_{i+1}$ then the temperature profile (T_i, T_{i+1}) is *not* superadiabatic and the checking procedure continues on to the next layer. However, if the above is not satisfied, at least one of the reported temperatures T_i or T_{i+1} must be erroneous. In order to determine which temperature is erroneous and correct the error if possible, it is necessary to use adjacent level data. The following algorithms are applied:

Table 19: Limit Values for Unreasonable Inversions over Thin Pressure Layers

Base Level (hPa)	Limit of maximum inversion (deg C)					
	0 - 30S		Area 30N - 60N / Area 30S - 60S		60N - 90N / 60S - 90S	
	Winter	Summer	Winter	Summer	Winter	Summer
1100 -1000	1.5	1.2	2.0	1.5	2.5	1.8
1000 - 850	1.5	1.2	2.0	1.5	2.5	1.8
850 - 700	1.4	1.2	1.8	1.5	2.2	1.8
700 - 500	1.2	1.2	1.5	1.5	1.8	1.8
500 - 400	1.2	1.2	1.5	1.5	1.8	1.8
400 - 300	1.2	1.2	1.5	1.5	1.8	1.8
300 - 250	1.4	1.4	1.5	1.5	1.8	1.8
250 - 200	1.8	1.8	1.8	1.8	1.8	1.8
200 - 150	2.2	2.2	2.2	2.2	2.2	2.2
150 - 100	2.6	2.6	2.6	2.6	2.6	2.6
100 - 70	3.0	3.0	3.0	3.0	3.0	3.0
70 - 50	3.5	3.5	3.5	3.5	3.5	3.5
50 - 30	4.5	4.5	4.5	4.5	4.5	4.5
30 - 20	5.5	5.5	5.5	5.5	5.5	5.5
20 - 10	6.5	6.5	6.5	6.5	6.5	6.5
10 - 7	7.5	7.5	7.5	7.5	7.5	7.5
7 - 5	8.5	8.5	8.5	8.5	8.5	8.5
5 - 3	8.5	8.5	8.5	8.5	8.5	8.5
3 - 2	8.5	8.5	8.5	8.5	8.5	8.5
2 - 1	8.5	8.5	8.5	8.5	8.5	8.5
1 - 0	8.5	8.5	8.5	8.5	8.5	8.5

Table 20: Limit Values for Unreasonable Inversions Over a Thick Pressure Layer

Base Level (hPa)	Limit of maximum inversion (deg C)					
	0 - 30N 0 - 30S		Area 30N - 60N Area 30S - 60S		60N - 90N 60S - 90S	
	Winter	Summer	Winter	Summer	Winter	Summer
1100 -1000	30	24	40	30	50	36
1000 - 850	30	24	40	30	50	36
850 - 700	14	12	18	15	22	18
700 - 500	12	12	15	15	18	18
500 - 400	12	12	15	15	18	18
400 - 300	12	12	15	15	18	18
300 - 250	14	14	15	15	18	18
250 - 200	18	18	18	18	18	18
200 - 150	26	22	26	22	26	22
150 - 100	29	26	29	26	29	26
100 - 70	32	30	32	35	32	30
70 - 50	35	35	35	35	35	35
50 - 30	35	35	35	35	35	35
30 - 20	35	35	35	35	35	35
20 - 10	35	35	35	35	35	35
10 - 7	35	35	35	35	35	35
7 - 5	35	35	35	35	35	35
5 - 3	35	35	35	35	35	35
3 - 2	35	35	35	35	35	35
2 - 1	35	35	35	35	35	35
1 - 0	35	35	35	35	35	35

Table 21: Allowances for Superadiabatic Lapse Rates

Level (hPa)	Correction (deg C)
1100 -1000	4.5
1000 - 850	3.5
850 - 700	2.5
700 - 500	1.5
500 - 400	1.0
400 - 0	0.5

- If $[T_{i+1} < T_{i-1}(p_{i+1}/p_{i-1})^{R/C_p}]$ and $[T_{i+2} \geq T_i(p_{i+2}/p_i)^{R/C_p}]$ then .... (-60;+1;0) fail T_{i+1}, T_i
- If $[T_{i+1} \geq T_{i-1}(p_{i+1}/p_{i-1})^{R/C_p}]$ and $[T_{i+2} < T_i(p_{i+2}/p_i)^{R/C_p}]$ then .... (-60;+1;0) fail T_{i+1}, T_i
- Otherwise, no definite conclusions can be drawn and .... (*;+1;0) fail T_{i+1}, T_i

Since the dewpoint depression is calculated from the dry bulb temperature and dewpoint, the confidence for the dewpoint depression is set to the minimum of the confidences already assigned for the temperature and dewpoint depression.

Recompute Mandatory Level Heights

The virtual temperatures are calculated for each level with the confidences for the temperature, dewpoint and pressure $\geq 65\%$ by

$$T^* = T_i * (1 + CO * e^{EL*Tx}/p_i) \quad (3)$$

where $Tx = TO - 1/Td_i$; $TO = 3.660322e^{-3}$; $EL = 5418.118466$ and $CO = 231.82582$. If the dewpoint is missing or has confidence < 65 %, then the temperature is used instead of the virtual temperature.

The heights are computed for each pressure level, starting from the station level using the hydrostatic equation

$$DZ_{ns-1} = (R/g) * [(T_{ns} + T_i)/2] * ln(p_{ns}/p_i) \quad (4)$$

where the subscript ns refers to the next lower significant level, the subscript i refers to the current level and DZ is the thickness between those levels. The computed heights are substituted for missing significant level heights. This test is not performed if either the station level is not found or no significant levels below 100 hPa are found. In addition, the recomputation of heights terminates if the depth of the layer $ns - i$ is greater than $P_{ns} * 0.3 + 20$ hPa. It also terminates at 100 hPa if no upper significant levels are found.

The reported heights are then compared with the computed heights:

$|Z_{com} - Z_{rep}| > TOL$ .... (-60;+1;0) fail Z_{rep}

The maximum allowed difference (TOL) depends upon height as follows:

- $Z_{com} < 6000$ m .... $TOL = 20$m
- $6000 \text{ m} \leq Z_{com} < 15000$ m .... $TOL = 20$m
- $Z_{com} \geq 15000$ m .... $TOL = 40$m

Hydrostatic Consistency Checks

The hydrostatic equation is used to check the vertical consistency between the reported temperatures and geopotential heights at the mandatory pressure levels. The hydrostatic constraint is one of the most powerful quality control tests since the geopotential heights at the mandatory levels are computed hydrostatically from the temperature profile. Moreover, the hydrostatic check reacts differently depending upon whether the error is in the temperature or geopotential height. For example, if the residuals from the two adjacent layers are large, of opposite sign and of approximately equal magnitude, a height error exists for the middle level. If the residuals are large, of the same sign, and of approximately equal magnitude, then temperature error exists at the middle level. The hydrostatic quality check proceeds as follows.

If possible, virtual temperatures T^* at the mandatory pressure levels are computed from (3). From the virtual temperatures (or the air temperatures T), the thicknesses between adjacent mandatory pressure levels are computed by

$$D_i = \frac{R_d}{g}\frac{T_i^* + T_{i+1}^*}{2}\ln(\frac{p_i}{p_{i+1}}). \tag{5}$$

Tolerances for the deviations between the reported and computed thickness are obtained by considering the most extreme temperature profiles in the layers between the mandatory pressure levels as shown in Figure 1. T_a^* is the warmest possible temperature profile assuming an inversion at level p_i and a dry adiabatic lapse rate in the layer. T_b^* is the coldest possible temperature profile, assuming a dry adiabatic lapse rate in the layer and an inversion at level p_{i+1}. The corresponding thicknesses, D_a and D_b are calculated from these temperature profiles. The tolerance is given by

$$TOL = K\left|\frac{D_a - D_b}{2}\right|, \tag{6}$$

where in practice K is given the value 0.75 since the very extreme temperature profiles T_a and T_b do not occur. The following restrictions on the testing tolerance TOL are used:

- Minimum value of TOL is 20 gpm
- Maximum value of TOL is 50 gpm below 400 mb.
- Maximum value of TOL is 80 gpm at and above 400 mb

The thickness departure or residual

$$E_i = Z_{i+1} - Z_i - D_i \tag{7}$$

is calculated provided the confidences of both Z_i and Z_{i+1} are at least 65%. Then, if

$$|E_i| > TOL \tag{8}$$

at least one of the values T_i, T_{i+1}, Z_i or Z_{i+1} must be erroneous.

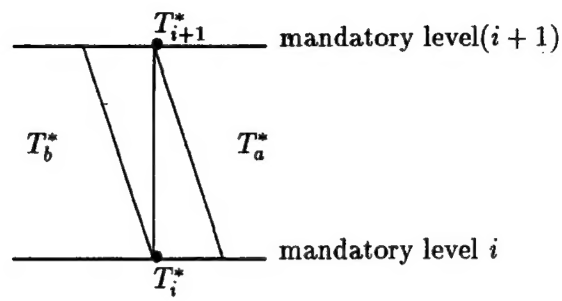

Figure 1: Temperature profile schematic showing warmest (T^*_a) and coldest (T^*_b) possible temperature

In order to isolate the errors, the following error index is computed for each error-marked layer:

$$F = \frac{E_i}{E_{i+1}}. \tag{9}$$

From the value of F, the following conclusions are made:

- $0.5 \leq F \leq 2.0$ .... (-30;0;0) for T_{i+1}, Td_{i+1}
- $-2.0 \leq F \leq -0.5$ .... (-30;0;0) for Z_{i+1}
- $|F| > 2.0$ .... (-30;0;0) for all heights Z_i and above
- $|F| < 0.5$ .... (*;+1;0) fail $T_i, T_{i+1}, Td_i, Td_{i+1}, Z_i and Z_{i+1}$

Vertical Wind Shear Checks

The vertical wind profiles are examined for excessive wind shear. The wind-speed difference between two adjacent mandatory pressure levels is required to be less than a tolerance determined by the sum of the two wind speeds. Limits are also placed on the maximum permitted sum of the two wind speeds as a function of the directional shear between the two levels. For the check of one mandatory pressure level wind, one more adjacent mandatory pressure level wind is needed.

The speed shear test is

- $|FF_1 - FF_2| > 20.6 + 0.275(FF_1 + FF_2)$ .... (*;+1;0) fail $dd_i, dd_{i+1}, FF_i, FF_{i+1}$

The directional shear test is

- $FF_1 + FF_2 > MAXSUM$ .... (*;+1;0) fail $dd_i, dd_{i+1}, FF_i, FF_{i+1}$
  where the limit, $MAXSUM$ is a function of the difference (directional shear) between dd_i and dd_{i+1} and is given by Table 22.

Table 22: Maximum Permitted Sum of Wind Speeds ($\mathrm{m\,s^{-1}}$)

	Directional shear (degrees)							
Layer (mb)	< 30	≥ 30	≥ 40	≥ 50	≥ 60	≥ 70	≥ 80	≥ 90
1000 - 850	-	72	61	57	53	49	46	41
700 - 200	-	110	84	77	70	63	52	50
150 - 0	-	72	61	57	53	49	46	41

Table 23: Conversion from Confidence Values to Quality Flags

Parameter	Confidence value (%)	Quality Flag	Comments
dd, FF	70 - 100	1	set according to minimum confidence
dd, FF	24 - 69	2	set according to minimum confidence
dd, FF	0 - 23	3	set according to minimum confidence
height	70 - 100	1	
or	70 - 100	4	indicates corrected value
temperature	70 - 100	6	indicates value substituted for missing
height	24 - 69	2	
or	0 - 69	5	corrected value; later flagged suspect
temperature	0 - 69	7	substituted value; later flagged suspect
dewpoint	70 - 100	1	
depression	24 - 69	2	
	0 - 23	3	
significant level	70 - 100	14	significant level pressure changed by CQC with height confidence $\geq 70\%$
pressure	0 - 69	15	significant level pressure changed by CQC with height confidence $< 70\%$

Quality Flag Assignments

The confidence values are converted to quality flags according to Table 23 with the flag definitions as specified in Table 1. The final wind QC flag is assigned according to the minimum of the wind direction and wind speed confidence values.

PILOT BALLOON REPORTS

Pilot balloons or PIBALs are provide observations of wind speed and direction as a function of height and/or pressure. The routines for checking PIBAL data are a subset of those used for radiosonde data. The pibal wind speeds are checked against climatological limits. Wind observations at the mandatory pressure levels are also checked for unrealistic vertical wind shear as described in radiosonde quality control section.

Table 24: Conversion from Confidence Values to Quality Flags

Confidence value (percent)	Quality Flag
70 - 100	1: good
24 - 69	2: suspect
0 - 23	3: bad

The confidence values are converted to quality flags according to Table 24. The final wind QC flag is assigned according to the minimum of the wind direction and wind speed confidence values.

SUMMARY

The operational atmospheric database at FNMOC provides quality controlled observations for use by the Navy's atmospheric analysis and prediction systems. Quality control is critically important since erroneous observations may adversely affect the quality of the numerical products, which in turn could potentially impact Fleet operations. As numerical weather prediction models become more advanced and the accuracy of the first guess increases, the sensitivity to errors in the observations becomes even greater. It will become increasingly important to develop rigorous, observing platform-specific quality control systems to extract the highest quality data possible.

The National Meteorological Center has demonstrated the effectiveness of a quality control system designed for a specific observing platform. Their Complex QC of radiosondes takes into account the types of rough errors found in radiosondes, and was specifically designed to detect and correct (if possible) those errors. A basic premise of CQC is that no final quality decisions are made until after all of the quality checks have been completed. Then, the results of the tests are examined and a final decision is made about the quality of an observation. The primary check in the CQC evaluates the hydrostatic consistency between the geopotential heights and temperatures. CQC also evaluates the consistency with the forecast first guess, with neighboring observations and with adjacent pressure levels.

This report describes the new, operational quality control system at FNMOC. The operational system contains the Complex QC from NMC as well as the more traditional objective QC based on procedures in use at ECMWF. The objective QC compares the observations against gross error limits and evaluates the internal consistency of the report. Radiosonde and pilot balloon reports also undergo extensive vertical consistency checks. For radiosondes, the vertical consistency checks include tests for unlikely lapse rates and inversions, and for hydrostatic consistency. Both radiosonde and pilot balloon reports are tested for unrealistic wind speed and directional shears.

Research efforts in the future will focus on developing innovative quality control techniques to handle problems such as the systematic radiative errors in radiosonde geopotential heights, and the horizontally correlated errors in the observations derived from the remote sensing of the atmosphere by satellites. The basic principles of Complex QC need to be applied to both the existing conventional observations as well as the new observing platforms scheduled for the future.

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